

PL-TR-97-2012

**APPLICATION OF PARALLEL COMPUTING
ALGORITHMS TO THREE-DIMENSIONAL MODELING
OF SEISMIC WAVES GENERATED BY COMPLEX
SOURCES IN INHOMOGENEOUS MEDIA**

**Charles G. Doll, Jr.
Joseph R. Matarese
Bertram Nolte**

**Earth Resources Laboratory
Department of Earth, Atmospheric, and
Planetary Sciences
Massachusetts Institute of Technology
42 Carleton Street
Cambridge, MA 02142**

15 January 1997

**Final Technical Report
14 July 1995–30 November 1996**

19970606 131

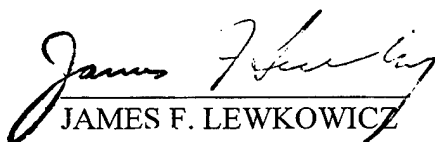
Approved for Public Release; Distribution Unlimited

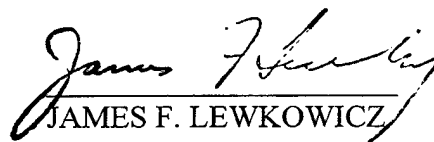


**PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AFB, MA 01731-3010**

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either express or implied, of the Air Force or U.S. Government.

This technical report has been reviewed and is approved for publication.


JAMES F. LEWKOWICZ
Alternate Contract Manager
Earth Sciences Division


JAMES F. LEWKOWICZ
Director
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify PL/IM, 29 Randolph Road, Hanscom AFB, MA 01731-3010. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 15 JAN 1997	3. REPORT TYPE AND DATES COVERED Final Technical 7/14/95-11/30/96		
4. TITLE AND SUBTITLE Application of Parallel Computing Algorithms to Three-Dimensional Modeling of Seismic Waves Generated by Complex Sources in Inhomogeneous Media		5. FUNDING NUMBERS F19628-95-K-0008 PE 62101F PR 7600 TA GM WU AA		
6. AUTHOR(S) Charles G. Doll, Jr. Joseph R. Matarese Bertram Nolte				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Earth Resources Laboratory Dept. of Earth, Atmospheric, and Planetary Sciences Massachusetts Institute of Technology 42 Carleton Street Cambridge, MA 02142		8. PERFORMING ORGANIZATION REPORT NUMBER 63614		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Phillips Laboratory 29 Randolph Road Hanscom AFB, MA 01731-3010 Contract Manager: Delaine Reiter/GPE		10. SPONSORING/MONITORING AGENCY REPORT NUMBER PL-TR-97-2012		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) We describe a hardware upgrade that was performed on the nCUBE 2 massively parallel computer at MIT's Earth Resources Laboratory. The upgrade involved the installation of additional memory, additional disk space, and an additional small nCUBE 2 computer. The reason for performing the upgrade was to provide ERL with a computational environment suitable for conducting large-scale 2-D and 3-D wave propagation simulations. We also describe two recent projects that were performed on the upgraded nCUBE 2. One project was a 3-D simulation of earthquake-generated ground motion in the Boston Basin. The other project was the development of a parallel irregular-grid modeling code which is well-suited for 2-D modeling of regional wave propagation in the presence of surface topography.				
14. SUBJECT TERMS Parallel computing; 3-D seismic wave propagation; earthquake ground motion			15. NUMBER OF PAGES 20	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	

TABLE OF CONTENTS

List of Contributing Scientists	iv
List of Previous and Related Contracts	iv
Bibliography of Publications Totally or Partially Supported by the Contract	iv
Introduction	1
Boston Basin Ground Motion Simulations	2
Irregular-Grid Modeling	7
References	11

List of Contributing Scientists

Charles G. Doll, Jr., Research Specialist, Massachusetts Institute of Technology.
Joseph R. Matarese, Visiting Scientist, Massachusetts Institute of Technology.
Bertram Nolte, Postdoctoral Associate, Massachusetts Institute of Technology.

List of Previous and Related Contracts

DARPA/AFGL Contract F19628-89-K-0020, "Regional Seismograms: Attenuation and Scattering", July 1989 to June 1991.
DARPA/AFPL Contract F19628-90-K-0057, "Research in Regional Seismology: The Effect of Anisotropy", August 1990 to July 1992.
DARPA/AFPL Contract F29601-91-K-DB15, "Research on Monitoring at Regional Distances", September 1991 to September 1993.
AFOSR Contract F49620-92-J-0413, "Basic Research in Nuclear Test Monitoring", July 1992 to July 1994.
AFOSR Contract F49620-93-1-0424 "Seismic Wave Radiation, Propagation and Event Location in Laterally Heterogeneous Media", July 1993 to December 1994.
AFOSR Grant F49620-94-1-0282, "Effect of 3D Heterogeneities and Topography on Seismic Wave Propagation and the Use of Empirical Green's Functions for Source Characterization and Discrimination", May 1994 to May 1996.
AFOSR Grant F49620-94-1-0273, "Characterization of Seismic Sources Using Empirical Green's Functions", July 1994 to June 1997.
AFOSR Grant F19628-95-C-0091, "Research on Seismic Monitoring at Regional Distances," June 1995 to June 1996.

Bibliography of Publications Totally or Partially Sponsored by the Contract

Olsen, K.B., R.J. Archuleta, and J.R. Matarese, 1995, Three-dimensional simulation of a magnitude 7.75 earthquake on the San Andreas Fault, *Science*, 270, 1628-1632.

1. INTRODUCTION

The 512-processor nCUBE 2 massively parallel computer, originally purchased in 1990, was upgraded to provide a capable computing environment for conducting large-scale 2-D and 3-D wave propagation simulations at the M.I.T. Earth Resources Laboratory (ERL). This upgrade involved three major components: (1) additional memory to allow simulations to be conducted on larger earth models; (2) additional disk space to allow detailed results of these simulations to be recorded for further analysis; and (3) an additional, small nCUBE 2 computer to be used ultimately as an Oracle database platform and to enable code development work to continue while large-scale simulations were occupying the big machine. The memory upgrade was performed in late December, 1995, and the disk upgrade and secondary nCUBE 2 installation were performed in the early spring of 1996.

Quantitatively, the memory upgrade increased the nCUBE 2's aggregate memory from 2.75 GB (gigabytes) to 5.375 GB, while the disk upgrade added a 100 GB high performance parallel filesystem. Before the memory upgrade, the nCUBE 2 had 448 processors with 4 MB (megabytes) of RAM each and 64 processors with 16 MB of RAM each. Given this configuration and the nature of the parallel finite difference modeling algorithm used in the wave simulations, the largest models that could be stored in memory, decomposed among all 512 processors, comprised 500 by 500 by 180 grid points. The upgrade has quadrupled the memory on roughly one-half the machine, i.e., the memory on 224 processors was increased from 4 MB to 16 MB. Therefore, the maximum model size has approximately doubled, for

example, a 1000 by 500 by 180 grid can now be stored.

In the course of conducting finite difference simulations, snapshots of the surface particle velocity field are typically recorded at every tenth-time step to provide a record of the surface ground motion. Given the duration of the simulations, the files containing the snapshot data grow to several hundred megabytes of data for each of the three Cartesian components of the particle velocity. The size of the disk array now makes it possible to archive the results of many simulations for comparative analysis. Also, snapshots of particle motion for the entire model volume can be saved, although at 100 MB per snapshot, not at the same rate as with the surface motion.

The following sections describe examples of wave propagation simulation performed on the upgraded nCUBE 2 computer.

2. BOSTON BASIN GROUND MOTION SIMULATIONS

In a previous study (Olsen *et al.*, 1995), a parallel version of a 3-D elastic finite-difference code was run on ERL's nCUBE 2 512-processor computer to simulate earthquake-generated ground motions in the Los Angeles Basin. The purpose was to study site amplification and scattering effects due to the 3-D structure of the basin. Here we report preliminary results of a similar study of the Boston Basin. Using the same finite difference code on our nCUBE 2, we simulated the 3-D ground motions within the Boston Basin generated by a hypothetical earthquake in the basin. The results of some initial simulations for the Boston

Basin suggested that the 3-D structure of the sedimentary basin has a significant effect on the complexity and amplification of surface ground motions. To better understand the basin effects, we have done subsequent simulations, described below, that compare the ground motions resulting from the 3-D basin model with those from a simple, 1-D model (layer over a half-space) that does not contain a 3-D sedimentary basin.

For each earth structure model, seismic waves were simulated for a hypothetical Mw 5.8 earthquake. The earthquake occurs along a vertical, strike-slip fault striking east-west with length 6.0 km and height 3.8 km. The fault centroid (point of initiation of the rupture) is placed at about a 5 km depth, and the fault was allowed to displace 1 meter to the west. For the simulation done with the 3-D basin model, the top of the fault lies 400 meters closer to the surface than for the 1-D model.

Each earth structure model (3-D and 1-D) was gridded with a cell size of 100 meters, which permits adequate sampling of wavelengths down to ~ 600 meters. Given the P propagation velocity of ~ 5000 meters/sec in the sedimentary rock of the basin, the peak frequency of the simulated ground motion is 8 Hz, with a center frequency of 4 Hz. The size of the basin model grid was 401 by 400 by 72 nodes in the east-west, north-south and depth directions, respectively.

The results of the ground motion simulations are shown in Figure 1 (3-D basin model) and Figure 2 (1-D two-layer model). From the top frames of the figures we see that the 3-D basin model produces peak ground velocities that are strongly variable with position on the

BOSTON BASIN

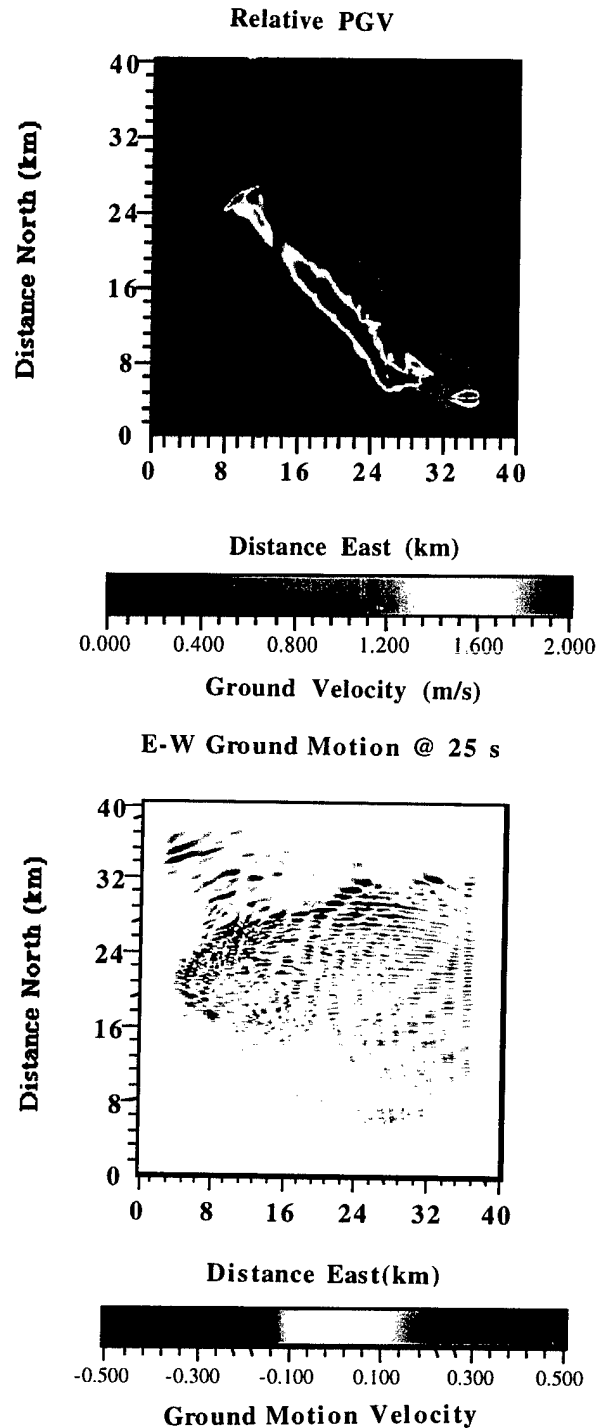


Figure 1: Snapshot of peak ground velocity at the surface of the Boston Basin resulting from an $M_w = 5.8$ earthquake (top). Ground motion at surface 25 seconds after start of rupture (bottom). The source of the earthquake is a vertical strike-slip fault displaced 1 m to the west. The fault has a length of 6 km, a height of 3.8 km, a centroid about 5 km deep, and is located at the southeast edge of the basin (note its lobed radiation pattern at the southeast corner of the basin). The earth model consists of a 3-D basin of sedimentary rock and irregular geometry surrounded by hard rock (granite).

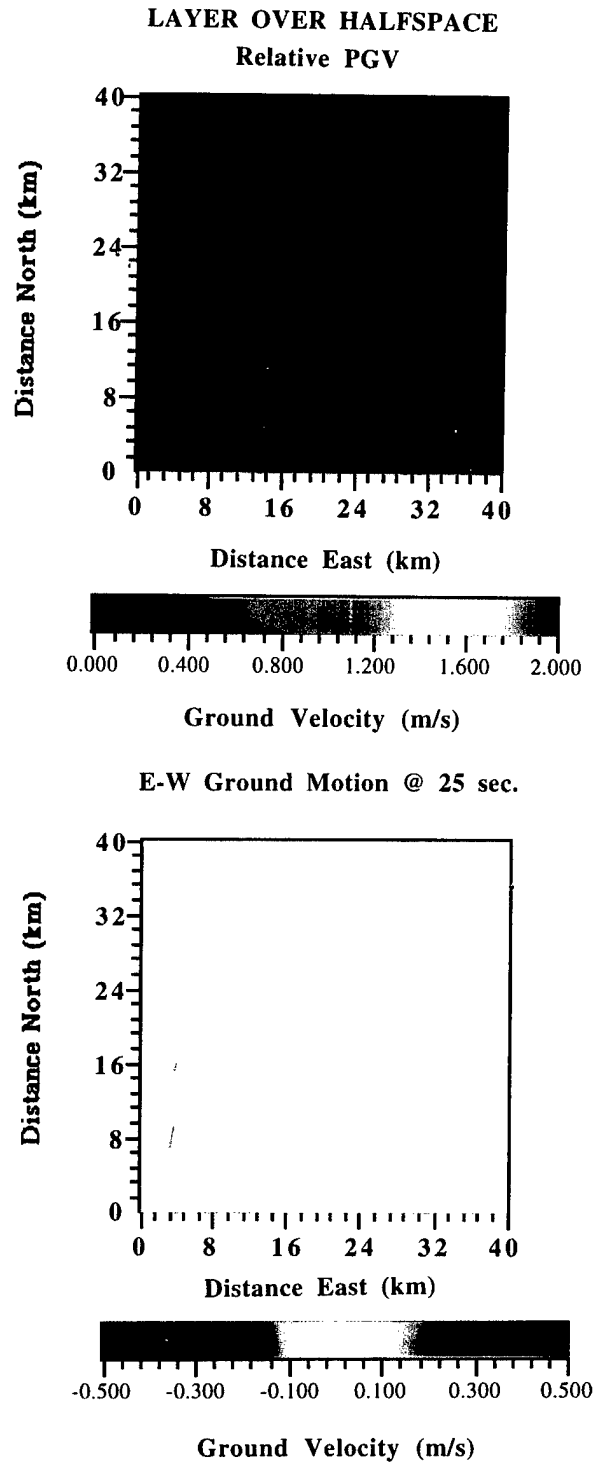


Figure 2: Peak ground velocity at the surface using a layer-over-a-half-space earth structure model (top). Snapshot of ground motion taken 25 seconds after rupture initiation (bottom). Source parameters of the hypothetical earthquake and overall dimensions of the earth model are the same as for the basin example in Figure 1. The layer-over-a-half-space model consists of a 2 km thick sedimentary rock layer over a hard rock (granite) half-space. Note the spatial uniformity of the peak ground velocity (top) and the simplicity of the ground motion (bottom).

earth's surface. In contrast, peak velocities for the 1-D model (Figure 2) are rather uniform. Also, on average, the 1-D model yields lower peak ground velocities. For the 3-D model (Figure 1), the high peak ground velocities forming the lobes of the radiation pattern in the immediate vicinity of the fault (southeast corner of the basin) is explained by the fact that the top of the fault is shallower than in the 1-D model.

The bottom frame of Figures 1 and 2 compare snapshots of the surface ground motion for the two models. Each snapshot corresponds to the wavefield 25 seconds after rupture initiation. We see that the complex pattern of ground motion associated with the basin model (bottom frame of Figure 1) stands in sharp contrast to the simple wavefield in the layer-over-a-half-space model (Figure 2). The wavefield in the 1-D model is attributed to the primary wavefront radiating outward from the source, while the wavefield in the 3-D basin model is a superposition of the primary wavefront with waves scattered by the basin structure.

Suggested future work includes expanding the volume of the basin model to ensure against possible contamination from artificial ground motion reflections generated at the absorbing boundaries. Further, a major modification of the finite difference code is the addition of anelastic attenuation operators. The interaction of anelastic attenuation with the effects of basin geometry (focusing and scattering of seismic waves) will yield a realistic estimate of the absolute levels of ground motion and refine the extent of ground motion variability associated with a sedimentary basin structure.

3. IRREGULAR-GRID MODELING

Another research project was the development of an irregular-grid method, based on a finite volume approximation, for the modeling of wave propagation in crustal models containing irregular interfaces and surface topography. This method has the advantage over finite differences in that interfaces in a model (including an irregular free surface) can be represented more accurately, and that the grid spacing can vary throughout the model and can thus be scaled to the wavespeeds.

We have implemented 2-D parallel versions of the algorithm for both SH and P-SV waves on the nCUBE 2 parallel computer of the Earth Resources Laboratory, using the Message Passing Interface (MPI). Using MPI guarantees easy portability of the codes. An efficient parallel implementation of the irregular-grid method was considerably more challenging than a parallel implementation of a finite difference algorithm, as an efficient grid decomposition (in terms of both load balancing and computation-to-communication ratio) is far more complicated for an unstructured grid.

We used the irregular-grid code to study the effect of surface topography on regional wave propagation. Figure 3a shows a 2-D crustal model with surface topography. Figure 3b shows the topography in more detail. The topography was obtained with the online profile maker from Cornell University's Middle East and North Africa Project database (<http://atlas.geo.cornell.edu>) for a profile in northern Iran.

We computed synthetic seismograms for this model with and without including the sur-

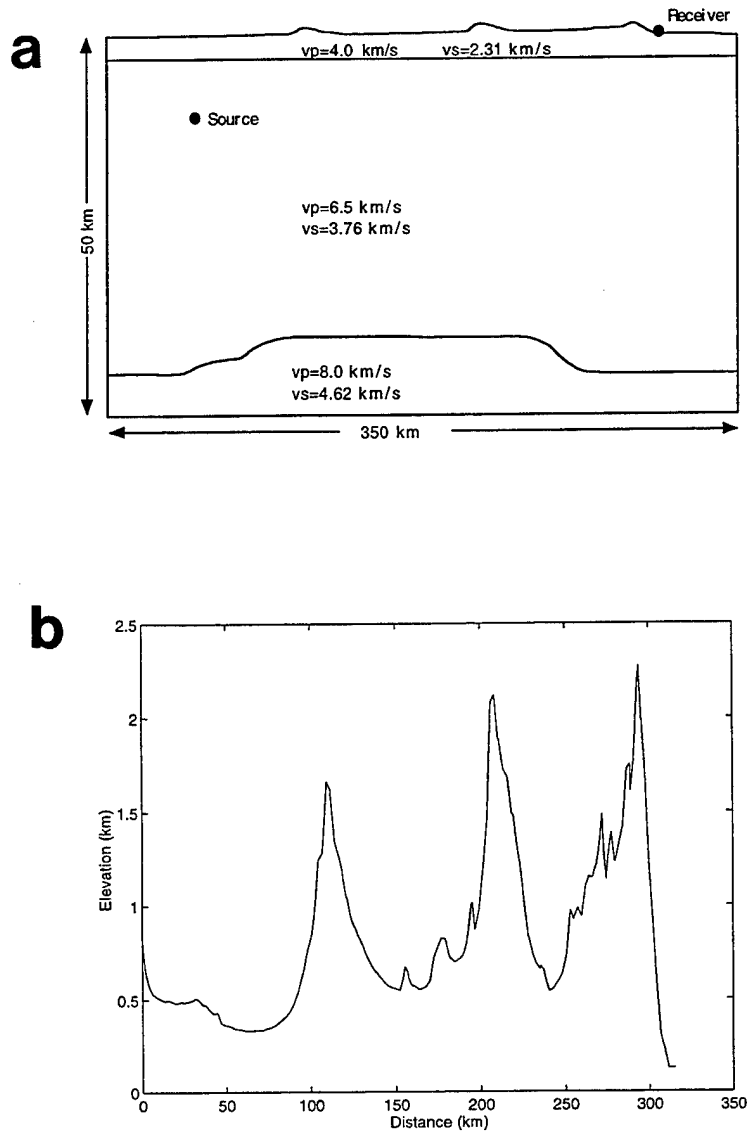


Figure 3: (a) Model with irregular surface topography used for the computation of synthetics.
 (b) Surface topography on a finer scale.

face topography. The results are shown in Figure 4. There are some distinct differences in the waveforms obtained for the two cases. In this example the most prominent differences are on the vertical component at larger arrival times (greater than 70 s). More arrivals with higher amplitudes are present in the case of surface topography. These arrivals are most likely due to surface waves that arise from scattering at the rough surface.

Our comparison demonstrates that a pronounced surface topography, such as is present in many regions (e.g., the Middle East), will have a distinct effect on observed waveforms, and should thus be included in the modeling. Our newly developed method provides a valuable tool for this task.

Suggested future work in the area of irregular-grid modeling includes the extension of the method to 3-D and its coupling to regular-grid finite differences, which will enable us to use irregular grids only in parts of the model, particular in the near-surface region. Such a hybrid approach would take advantage of the strong points of either method and thus maximize the overall efficiency.

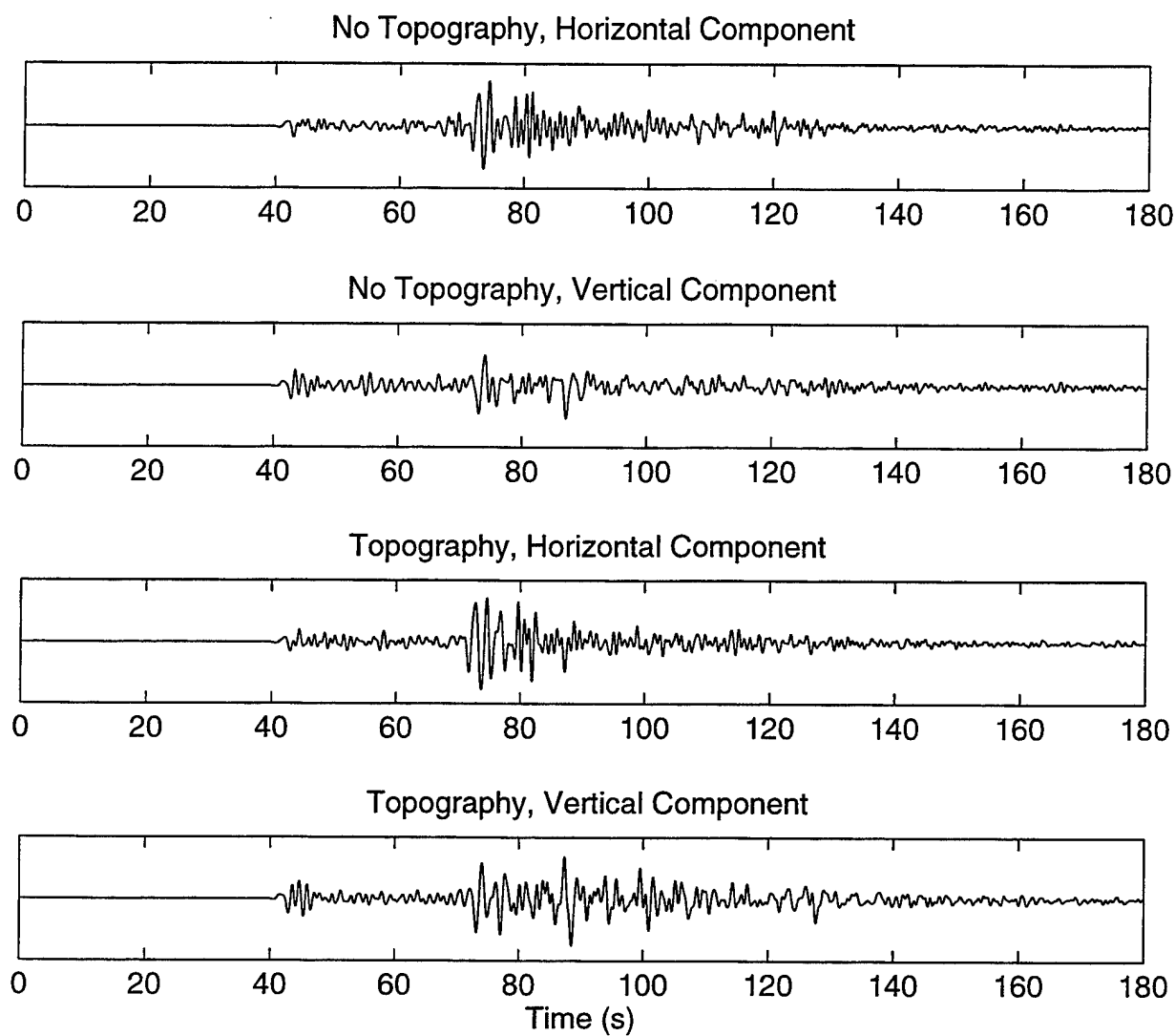


Figure 4: Synthetic waveforms on horizontal and vertical components for the model in Figure 3 and for an equivalent model with a flat surface.

REFERENCES

Olsen, K.B., R.J. Archuleta, and J.R. Matarrese, 1995, Three-dimensional simulation of a magnitude 7.75 earthquake on the San Andreas Fault, *Science*, 270, 1628–1632.

THOMAS AHRENS
SEISMOLOGICAL LABORATORY 252-21
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CA 91125

RALPH ALEWINE
NTPO
1901 N. MOORE STREET, SUITE 609
ARLINGTON, VA 22209

SHELTON ALEXANDER
PENNSYLVANIA STATE UNIVERSITY
DEPARTMENT OF GEOSCIENCES
537 DEIKE BUILDING
UNIVERSITY PARK, PA 16801

MUAWIA BARAZANGI
INSTITUTE FOR THE STUDY OF THE CONTINENTS
3126 SNEE HALL
CORNELL UNIVERSITY
ITHACA, NY 14853

T.G. BARKER
MAXWELL TECHNOLOGIES
8888 BALBOA AVE.
SAN DIEGO, CA 92123-1506

DOUGLAS BAUMGARDT
ENSCO INC.
5400 PORT ROYAL ROAD
SPRINGFIELD, VA 22151

THERON J. BENNETT
MAXWELL TECHNOLOGIES
11800 SUNRISE VALLEY DRIVE SUITE 1212
RESTON, VA 22091

WILLIAM BENSON
NAS/COS
ROOM HA372
2001 WISCONSIN AVE. NW
WASHINGTON, DC 20007

JONATHAN BERGER
UNIVERSITY OF CA, SAN DIEGO
SCRIPPS INSTITUTION OF OCEANOGRAPHY IGPP, 0225
9500 GILMAN DRIVE
LA JOLLA, CA 92093-0225

ROBERT BLANDFORD
AFTAC
1300 N. 17TH STREET
SUITE 1450
ARLINGTON, VA 22209-2308

STEVEN BRATT
NTPO
1901 N. MOORE STREET, SUITE 609
ARLINGTON, VA 22209

RHETT BUTLER
IRIS
1200 NEW YORK AVE., NW
SUITE 800
WASHINGTON, DC 20005

LESLIE A. CASEY
DOE
1000 INDEPENDENCE AVE. SW
NN-20
WASHINGTON, DC 20585-0420

CATHERINE DE GROOT-HEDLIN
UNIVERSITY OF CALIFORNIA, SAN DIEGO
INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS
8604 LA JOLLA SHORES DRIVE
SAN DIEGO, CA 92093

STANLEY DICKINSON
AFOSR
110 DUNCAN AVENUE, SUITE B115
BOLLING AFB
WASHINGTON, D.C. 20332-001

DIANE I. DOSER
DEPARTMENT OF GEOLOGICAL SCIENCES
THE UNIVERSITY OF TEXAS AT EL PASO
EL PASO, TX 79968

RICHARD J. FANTEL
BUREAU OF MINES
DEPT OF INTERIOR, BLDG 20
DENVER FEDERAL CENTER
DENVER, CO 80225

MARK D. FISK
MISSION RESEARCH CORPORATION
735 STATE STREET
P.O. DRAWER 719
SANTA BARBARA, CA 93102-0719

ROBERT GEIL
DOE
PALAIS DES NATIONS, RM D615
GENEVA 10, SWITZERLAND

LORI GRANT
MULTIMAX, INC.
311C FOREST AVE. SUITE 3
PACIFIC GROVE, CA 93950

HENRY GRAY
SMU STATISTICS DEPARTMENT
P.O. BOX 750302
DALLAS, TX 75275-0302

DAVID HARKRIDER
PHILLIPS LABORATORY
EARTH SCIENCES DIVISION
29 RANDOLPH ROAD
HANSCOM AFB, MA 01731-3010

THOMAS HEARN
NEW MEXICO STATE UNIVERSITY
DEPARTMENT OF PHYSICS
LAS CRUCES, NM 88003

DONALD HELMBERGER
CALIFORNIA INSTITUTE OF TECHNOLOGY
DIVISION OF GEOLOGICAL & PLANETARY SCIENCES
SEISMOLOGICAL LABORATORY
PASADENA, CA 91125

ROBERT HERRMANN
ST. LOUIS UNIVERSITY
DEPARTMENT OF EARTH & ATMOSPHERIC SCIENCES
3507 LACLEDE AVENUE
ST. LOUIS, MO 63103

ANTHONY IANNACCHIONE
BUREAU OF MINES
COCHRANE MILL ROAD
PO BOX 18070
PITTSBURGH, PA 15236-9986

THOMAS JORDAN
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
EARTH, ATMOSPHERIC & PLANETARY SCIENCES
77 MASSACHUSETTS AVENUE, 54-918
CAMBRIDGE, MA 02139

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 808, MS L-221
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 808, MS L-208
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 808, MS L-195
LIVERMORE, CA 94551

I. N. GUPTA
MULTIMAX, INC.
1441 MCCORMICK DRIVE
LARGO, MD 20774

IAN MACGREGOR
NSF
4201 WILSON BLVD., ROOM 785
ARLINGTON, VA 22230

MICHAEL HEDLIN
UNIVERSITY OF CALIFORNIA, SAN DIEGO
SCRIPPS INSTITUTION OF OCEANOGRAPHY IGPP, 0225
9500 GILMAN DRIVE
LA JOLLA, CA 92093-0225

EUGENE HERRIN
SOUTHERN METHODIST UNIVERSITY
DEPARTMENT OF GEOLOGICAL SCIENCES
DALLAS, TX 75275-0395

VINDELL HSU
HQ/AFTAC/TTR
1030 S. HIGHWAY A1A
PATRICK AFB, FL 32925-3002

RONG-SONG JIH
HQ DSWA/PMP/CTBT
6801 TELEGRAPH ROAD
ALEXANDRIA, VA 22310-3398

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 808, MS L-200
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
LLNL
PO BOX 808, MS L-175
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 808, MS L-202
LIVERMORE, CA 94551

LAWRENCE LIVERMORE NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 808, MS L-205
LIVERMORE, CA 94551

THORNE LAY
UNIVERSITY OF CALIFORNIA, SANTA CRUZ
EARTH SCIENCES DEPARTMENT
EARTH & MARINE SCIENCE BUILDING
SANTA CRUZ, CA 95064

DONALD A. LINGER
DNA
6801 TELEGRAPH ROAD
ALEXANDRIA, VA 22310

✓ LOS ALAMOS NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 1663, MS F665
• LOS ALAMOS, NM 87545

LOS ALAMOS NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 1663, MS C335
LOS ALAMOS, NM 87545

KEITH MCLAUGHLIN
MAXWELL TECHNOLOGIES
8888 BALBOA AVE.
SAN DIEGO, CA 92123-1506

RICHARD MORROW
USACDA/VI
320 21ST STREET, N.W.
WASHINGTON, DC 20451

JAMES NI
NEW MEXICO STATE UNIVERSITY
DEPARTMENT OF PHYSICS
LAS CRUCES, NM 88003

✓ PACIFIC NORTHWEST NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 999, MS K6-48
✓ RICHLAND, WA 99352

✓ PACIFIC NORTHWEST NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 999, MS K6-40
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 999, MS K5-12
RICHLAND, WA 99352

ANATOLI L. LEVSHIN
DEPARTMENT OF PHYSICS
UNIVERSITY OF COLORADO
CAMPUS BOX 390
BOULDER, CO 80309-0309

LOS ALAMOS NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 1663, MS F659
LOS ALAMOS, NM 87545

LOS ALAMOS NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 1663, MS D460
LOS ALAMOS, NM 87545

GARY MCCARTOR
SOUTHERN METHODIST UNIVERSITY
DEPARTMENT OF PHYSICS
DALLAS, TX 75275-0395

BRIAN MITCHELL
DEPARTMENT OF EARTH & ATMOSPHERIC SCIENCES
ST. LOUIS UNIVERSITY
3507 LACLEDE AVENUE
ST. LOUIS, MO 63103

JOHN MURPHY
MAXWELL TECHNOLOGIES
11800 SUNRISE VALLEY DRIVE SUITE 1212
RESTON, VA 22091

JOHN ORCUTT
INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS
UNIVERSITY OF CALIFORNIA, SAN DIEGO
LA JOLLA, CA 92093

PACIFIC NORTHWEST NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 999, MS K7-34
RICHLAND, WA 99352

PACIFIC NORTHWEST NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
PO BOX 999, MS K6-84
RICHLAND, WA 99352

FRANK PILOTTE
HQ/AFTAC/TT
1030 S. HIGHWAY A1A
PATRICK AFB, FL 32925-3002

KEITH PRIESTLEY
DEPARTMENT OF EARTH SCIENCES
UNIVERSITY OF CAMBRIDGE
MADINGLEY RISE, MADINGLEY ROAD
CAMBRIDGE, CB3 0EZ UK

PAUL RICHARDS
COLUMBIA UNIVERSITY
LAMONT-DOHERTY EARTH OBSERVATORY
PALISADES, NY 10964

CHANDAN SAIKIA
WOODWARD-CLYDE FEDERAL SERVICES
566 EL DORADO ST., SUITE 100
PASADENA, CA 91101-2560

SANDIA NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
DEPT. 5791
MS 0567, PO BOX 5800
ALBUQUERQUE, NM 87185-0567

SANDIA NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
DEPT. 5704
MS 0655, PO BOX 5800
ALBUQUERQUE, NM 87185-0655

THOMAS SERENO JR.
SCIENCE APPLICATIONS INTERNATIONAL
CORPORATION
10260 CAMPUS POINT DRIVE
SAN DIEGO, CA 92121

ROBERT SHUMWAY
410 MRAK HALL
DIVISION OF STATISTICS
UNIVERSITY OF CALIFORNIA
DAVIS, CA 95616-8671

DAVID SIMPSON
IRIS
1200 NEW YORK AVE., NW
SUITE 800
WASHINGTON, DC 20005

BRIAN SULLIVAN
BOSTON COLLEGE
INSITUTE FOR SPACE RESEARCH
140 COMMONWEALTH AVENUE
CHESTNUT HILL, MA 02167

NAFI TOKSOZ
EARTH RESOURCES LABORATORY, M.I.T.
42 CARLTON STREET, E34-440
CAMBRIDGE, MA 02142

JAY PULLI
BBN
1300 NORTH 17TH STREET
ROSSLYN, VA 22209

DAVID RUSSELL
HQ AFTAC/TTR
1030 SOUTH HIGHWAY A1A
PATRICK AFB, FL 32925-3002

SANDIA NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
DEPT. 5704
MS 0979, PO BOX 5800
ALBUQUERQUE, NM 87185-0979

SANDIA NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
DEPT. 9311
MS 1159, PO BOX 5800
ALBUQUERQUE, NM 87185-1159

SANDIA NATIONAL LABORATORY
ATTN: TECHNICAL STAFF (PLS ROUTE)
DEPT. 5736
MS 0655, PO BOX 5800
ALBUQUERQUE, NM 87185-0655

AVI SHAPIRA
SEISMOLOGY DIVISION
THE INSTITUTE FOR PETROLEUM RESEARCH AND
GEOPHYSICS
P.O.B. 2286, NOLON 58122 ISRAEL

MATTHEW SIBOL
ENSCO, INC.
445 PINEDA COURT
MELBOURNE, FL 32940

JEFFRY STEVENS
MAXWELL TECHNOLOGIES
8888 BALBOA AVE.
SAN DIEGO, CA 92123-1506

DAVID THOMAS
ISEE
29100 AURORA ROAD
CLEVELAND, OH 44139

LAWRENCE TURNBULL
ACIS
DCI/ACIS
WASHINGTON, DC 20505

GREG VAN DER VINK
IRIS
1200 NEW YORK AVE., NW
SUITE 800
WASHINGTON, DC 20005

TERRY WALLACE
UNIVERSITY OF ARIZONA
DEPARTMENT OF GEOSCIENCES
BUILDING #77
TUCSON, AZ 85721

JAMES WHITCOMB
NSF
NSF/ISC OPERATIONS/EAR-785
4201 WILSON BLVD., ROOM 785
ARLINGTON, VA 22230

JIANG XIE
COLUMBIA UNIVERSITY
LAMONT DOHERTY EARTH OBSERVATORY
ROUTE 9W
PALISADES, NY 10964

OFFICE OF THE SECRETARY OF DEFENSE
DDR&E
WASHINGTON, DC 20330

TACTEC
BATTELLE MEMORIAL INSTITUTE
505 KING AVENUE
COLUMBUS, OH 43201 (FINAL REPORT)

PHILLIPS LABORATORY
ATTN: GPE
29 RANDOLPH ROAD
HANSCOM AFB, MA 01731-3010

PHILLIPS LABORATORY
ATTN: PL/SUL
3550 ABERDEEN AVE SE
KIRTLAND, NM 87117-5776 (2 COPIES)

FRANK VERNON
UNIVERSITY OF CALIFORNIA, SAN DIEGO
SCRIPPS INSTITUTION OF OCEANOGRAPHY IGPP, 0225
9500 GILMAN DRIVE
LA JOLLA, CA 92093-0225

DANIEL WEILL
NSF
EAR-785
4201 WILSON BLVD., ROOM 785
ARLINGTON, VA 22230

RU SHAN WU
UNIVERSITY OF CALIFORNIA SANTA CRUZ
EARTH SCIENCES DEPT.
1156 HIGH STREET
SANTA CRUZ, CA 95064

JAMES E. ZOLLWEG
BOISE STATE UNIVERSITY
GEOSCIENCES DEPT.
1910 UNIVERSITY DRIVE
BOISE, ID 83725

DEFENSE TECHNICAL INFORMATION CENTER
8725 JOHN J. KINGMAN ROAD
FT BELVOIR, VA 22060-6218 (2 COPIES)

PHILLIPS LABORATORY
ATTN: GPBP
29 RANDOLPH ROAD
HANSCOM AFB, MA 01731-3010

PHILLIPS LABORATORY
ATTN: RESEARCH LIBRARY/TL
5 WRIGHT STREET
HANSCOM AFB, MA 01731-3004